CLIMATE CHANGE IMPACTS ON GREAT LAKES LEVELS AND FLOWS

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ABSTRACT: The availability of adequate fresh water supplies is potentially one of the United States most serious long-range problems. The U.S.-Canada International Joint Commission is studying the impact of changing climate on the water levels of the Laurentian Great Lakes. As part of this, the Great Lakes Environmental Research Laboratory and the Canadian Climate Centre combined global circulation model outputs with hydrological models. This enables them to estimate changes in the net basin water supplies to the Great Lakes under a double-CO_2 scenario. GLERL ran these net basin supplies through a hydrologic response (routing) model of the unregulated lakes and used modified regulation plans for Lakes Superior and Ontario to determine resulting changes in lake levels and flows. The anticipated 20 to 100 percent decrease in individual lake net basin supplies substantially lowers water levels by 0.5 to 2 meters. The lower lake levels accompany significant decreases in flows of the connecting channels and St. Lawrence River. These results would have major environmental and socioeconomic implications and would require a change in the present water management strategies for the Great Lakes. The change in levels and flows is also compared with extreme scenarios based upon the present climate to put the results into perspective.
KEY TERMS: Great Lakes, climate change, water levels, regulation

INTRODUCTION

The availability of adequate fresh water supplies is potentially one of the nation's most serious long range problems. This is a major issue for the Great Lakes which contain about 95 percent of the U.S. fresh surface water. This water resource is shared between the U.S. and Canada and supports many important uses including hydropower, industry, navigation, municipal, recreation, and fish and wildlife habitat. The major indicators of water quantity for the Great Lakes are the lake levels of the five Great Lakes and Lake St. Clair and the flows in the connecting channels. The existing uses of the Great Lakes waters have been based on the historic range of water level fluctuations, about 2 meters from record high to record low, on a monthly basis. There is a potential for much greater stress on the water resources, represented by lower lake levels, under projected global warming scenarios. As part of their Great Lakes Levels Reference Study, the International Joint Commission (IJC) has sponsored a series of studies to assess potential future lake level fluctuations. This

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study describes the effect of climate change on Great Lakes water levels and flows using water supplies determined from the Canadian Climate Center's global climate model outputs (Croley, 1992) and compares the results with levels based on dry climate analogue scenarios.

THE GREAT LAKES SYSTEM

The Great Lakes Basin is shown in Figure 1. The basin has a total land area of 534,000 km^2 with a water surface of 247,000 km^2. Two of the lakes, Superior and Ontario, are regulated by controlling their outflows according to approved regulation plans under the auspices of the IJC. In addition to this regulation, the hydraulics of the system result in a major backwater effect between Lakes Michigan-Huron and St. Clair, and between Lakes St. Clair and Erie. Lakes Michigan and Huron are considered to be one lake hydraulically, as they are joined by the deep Straits of Mackinac. There are two interbasin diversions, the Lake Michigan Diversion at Chicago which diverts 91 m^3s^{-1} into the Mississippi River Basin, and the Long Lac and Ogoki Diversions which bring 153 m^3s^{-1} from the Hudson Bay watershed into Lake Superior. There is also the Welland Diversion, an intrabasin diversion, between Lakes Erie and Ontario, flowing 245 m^3s^{-1}.

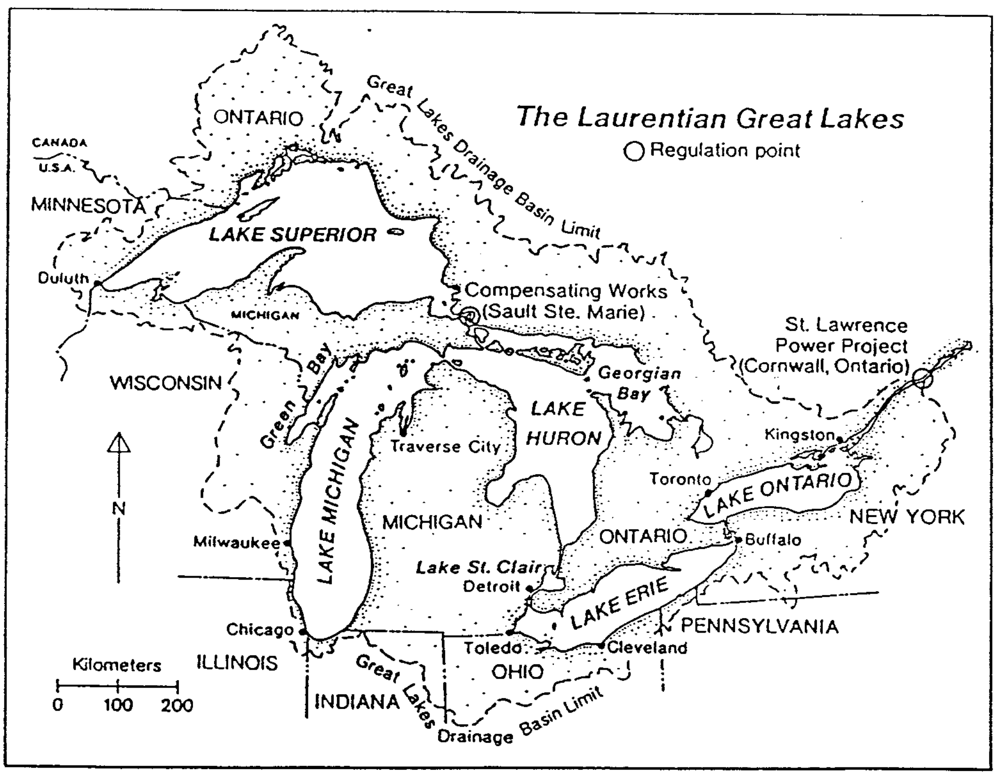

Figure 1. The Laurentian Great Lakes Basin

The Great Lakes water levels have been recorded since the early 1800's with consistent high quality measurements since 1860. The annual lake levels represent the long term variability of the system. Record low levels were set in 1934 and 1964 for the lower lakes and in 1925 for Lake Superior. The last occurrence of low levels was in the mid-1960's. Since that time, lake levels have generally ranged from average to record high conditions.

Changes in the Great Lakes hydraulic and hydrologic regime which have occurred over time are reflected in the recorded water levels and outflows. The principal changes to the Great Lakes system have primarily been anthropogenic and include changes in the amount of diversions into, within, and out of the system, modifications to the connecting channels and the St. Lawrence River, and the construction of control structures at the outlets of Lake Superior and Lake Ontario. In addition to these changes, which can be related to a specific point in time, there have been changes in the runoff from the land surface area due to deforestation, urbanization, etc.; increases in consumptive uses of water within the basin; and the movement of the earth's crust within the basin. These latter items have been progressive over time and have resulted in a gradual change in the water surface elevations of the individual lakes.

In order to have a common basis which represents "present conditions" by which the effects of various climate change scenarios can be evaluated, a set of lake levels and flows have been developed which reflect a consistent hydraulic regime in the Great Lakes-St. Lawrence River system over time. This hydraulic regime is defined by the diversion rates into and out of the system, the time series of water supplies to the system, outlet conditions of each lake, flow retardation due to ice or weeds in the connecting channels, and initial starting elevations for the simulation. These conditions are summarized in Table 1. The simulated "present conditions" monthly mean levels and flows were compared to recorded monthly mean levels and flows for 1974-1988 and were found to be highly correlated with low root mean squared error.

Previous studies performed by the Great Lakes Environmental Research Laboratory for the Environmental Protection Agency have estimated the change in net basin supplies, lake levels and outflows under a changed climate based on several scenarios generated by different global climate models (Croley and Hartmann, 1989). Net basin supply is defined in equation (1) as:

$$NBS = P + R - E \tag{1}$$

where P is over lake precipitation, R is the runoff into the lake from its basin, and E is the evaporation from the lake surface.

However, the analysis of the impact on levels and flows was hampered by numerical instabilities in the regulation plans of Lake Superior and Lake Ontario. These regulation plans have only been developed and evaluated with the sequence of water supplies experienced from 1900 to 1986 for Lake Superior (ILSBC, 1981), and 1860 to 1954 for Lake Ontario (ISLRBC, 1963). The plans do not embody rules of operation for conditions of supplies more extreme than those experienced in the past, such as those anticipated under climate change. With the current regulation plans, under climate change conditions, the minimum outflow limitations specify outflows larger than the supply of water to the lakes, and "mining" of the

Table 1. "Present Conditions" Hydraulic Regime	
WATER SUPPLIES	coordinated monthly net basin supplies for 1900 through 1989 from the Corps of Engineers and Environment Canada
DIVERSION RATES	1) a constant Chicago diversion of 91 m^3s^{-1} out of Lake Michigan 2) a constant Long Lac and Ogoki diversion of 153 cfs into Lake Superior, the average of recorded monthly flows 1944 to 1989 3) monthly mean values of the Welland Canal diversion from Lake Erie into Lake Ontario based on the recorded monthly flows March 1973 to December 1989
OUTLET CONDITIONS	1) Lake Superior outflows determined in accordance with Plan 77-A as modified 2) Lake Ontario outflows determined in accordance with Plan 1958-D as modified, with discretionary actions 3) Lake Huron and Lake St. Clair channel conditions since the completion of the 27 foot navigation channel dredging in 1962 4) Niagara River channel conditions representative of the period 1974-1986
ICE AND WEED RETARDATION	1) St. Clair and Detroit River monthly median retardation values based on computed retardation from 1962 to 1989 2) Niagara River monthly average values of weed retardation computed for 1974 through 1989 and median ice retardation values as computed from 1974 through 1989
INITIAL STARTING ELEVATIONS	long-term January monthly means for initial starting elevations

lakes' water occurs. Operationally, when extreme supplies have been experienced and the plans' specifed outflows deemed unsatisfactory, the International Joint Commission and its Boards of Control, under the authority of the Boundary Waters Act of 1909, have specified the outflows to best meet the needs of the various Great Lakes interests. This decision making process is complex and not easily incorporated into simple rules of operation which can be encoded in the regulation software programs.

However, for the purposes of simulating levels and flows under sequences of extreme supplies, some operational rules must be incorporated into the existing regulation plans. For the purposes of this study, stage-discharge relationships representing the natural outlet conditions of Lakes Superior and Ontario prior to project development were used to specify outflows when the levels of the lakes fell below designated elevations. For Lake Superior, the outflow was specifed by the relationship expressed in equation (2) (Southam and Larsen, 1990) whenever the lake's level fell below 600.5 feet on the International Great Lakes Datum of 1955 (IGLD 1955), and this outflow was less than that specifed by the unmodified regulation plan.

$$Q_S = 4901\ (\mathit{Pt.\ Iroquois} - 593.99)^{1.5} \tag{2}$$

In equation (2), Q_S is the Lake Superior outflow in cubic feet per second and *Pt. Iroquois* is the level in feet of Lake Superior at Pt. Iroquois, Michigan on IGLD 1955. English units are given here as both the U.S. and Canadian versions of the regulation plans are executed in

English units. This modification to Lake Superior's regulation plan is actually an interpretation of Criterion C of the 1979 Supplementary Orders of Approval (IJC, 1979) which reads:

> "To guard against unduly low levels in Lake Superior, the outflow from Lake Superior shall be reduced whenever, in the opinion of the Board, such reductions are necessary in order to prevent unduly low stages of water in Lake Superior, and shall fix the amounts of such reductions; provided that whenever the monthly mean level of the Lake is less than 600.5 IGLD (1955), the total discharge permitted shall be no greater than that which it would have obtained under the discharge conditions which obtained prior to 1887."

A similar rule was incorporated into Lake Ontario's regulation plan such that whenever the level of the lake falls below 242.77 feet IGLD 1955, the lake's outflows are based upon the relationship expressed in equation (3) which contains a correction for isostatic rebound (Dumont and Fay, 1990).

$$Q_O = 3430\ (Oswego - (0.0055\ (year - 1903))\ -227.45)^{1.5} \qquad (3)$$

In equation (3), Q_O is the Lake Ontario outflow in cubic feet per second, *Oswego* is the level in feet of Lake Ontario at Oswego, New York on IGLD 1955, and *year* is the calendar year. The year 1992 was assumed for the equation to represent present conditions yielding equation (4):

$$Q_O = 3430\ (Oswego - 227.94)^{1.5} \qquad (4)$$

Although there is no explicit guidance in the Orders of Approval for Lake Ontario regulation under extreme low supply conditions, as there is in the Orders of Approval for Lake Superior, this rule seems reasonable as no interest is worse off than if the project had not been built. The elevation 242.77 feet IGLD 1955 was selected as this is the lower regulation limit of the lake for April through November (ISLRBC, 1963).

SCENARIO DEVELOPMENT AND RESULTS

Climate Change Scenario

As discussed in Croley (1992), water supplies to the Great Lakes under a changed climate were developed based upon simulations from the Canadian Climate Center general circulation model. The Canadian Climate Center provided the results of a "present climate" (1 x CO_2) simulation and a "changed-climate" (2 x CO_2) simulation. From these simulations, the Great Lakes Environmental Research Laboratory computed ratios of the 2 x CO_2 to 1 x CO_2 monthly average air temperature, precipitation, humidity, cloud cover, and monthly average differences of windspeeds. These ratios and differences were applied to the historical data of 1948 to 1988 to represent a changed climate. The changed data was input into hydrological models of the 121 Great Lakes watersheds to estimate "steady-state" conditions under a changed climate. The steady-state results were then compared to results from the hydrologic models with unchanged historical data as input.

Levels and flows were then obtained by routing the net basin supplies derived from the climate change scenario through the modified regulation plans, with the conditions described in Table 1, until steady-state conditions were obtained. The relative differences in the average annual steady-state net basin supplies, levels, and flows under the changed climate from the present conditions were computed and are summarized in Table 2. The relative differences in levels and flows found in this study are compared to previous results presented by Hartmann (1990) in Tables 3 and 4.

Table 2. Relative Differences in Average Annual Steady-State Net Basin Supplies, Levels, and Flows Under a Changed Climate

Lake	NBS (mm, %)	Levels (m)	Flows (m^3s^{-1})
Lake Superior	-187 (-21%)	-0.30	-335 (-16%)
Lakes Michigan-Huron	-497 (-52%)	-1.76	-1909 (-35%)
Lake St. Clair	-2850 (-65%)	-1.60	-2012 (-36%)
Lake Erie	-818 (-101%)	-1.49	-2662 (-43%)
Lake Ontario	-852 (-42)	-1.40	-3048 (-42%)

Table 3. Relative Differences in Average Annual Steady-State Levels (m)

Lake	GISS[3]	GFDL[4]	OSU[5]	CCC[6]
Lake Superior	-0.46	-	-0.47	-0.30
Lakes Michigan-Huron	-1.31	-2.48	-0.99	-1.76
Lake St. Clair	-1.21	-2.12	-0.87	-1.60
Lake Erie	-1.16	-1.91	-0.79	-1.49
Lake Ontario	-	-	-	-1.40

[3] Results based on GCM output from Goddard Institute for Space Studies (Hartmann, 1990)
[4] " " Geophysical Fluid Dynamics Laboratory (Hartmann, 1990)
[5] " " Oregon State University (Hartmann, 1990)
[6] " " Canadian Climate Center

Table 4. Relative Differences in Average Annual Steady-State Outflows (m^3s^{-1})				
Lake	GISS[3]	GFDL[4]	OSU[5]	CCC[6]
Lake Superior	-36	-	-422	-335
Lakes Michigan-Huron	-1434	-	-1159	-1909
Lake St. Clair	-1512	-	-1199	-2012
Lake Erie	-2047	-	-1461	-2662
Lake Ontario	-	-	-	-3048

Climate Analog Scenarios

Historical climatic data from the 1860-1988 period were used to develop a set of low 5-year water supply scenarios based upon recorded climatic data and lake evaporation and large basin runoff models. These analog scenarios are compared with the Canadian Climate Center global climate model outputs to indicate the relative severity of the global warming scenarios with potential dry outcomes based upon the present climate. The climate analog scenarios build upon the work by Quinn and Changnon (1989) and consist of 5-year climate blocks based upon a weighted precipitation for the upper Great Lakes. Upper Great Lakes precipitation values were developed to account for the effect of changes in lake precipitation for Lakes Superior, Michigan-Huron, and Erie on the net basin supplies and water levels for Lakes Michigan-Huron and Erie. A precipitation index using a weighted 5-year upper Great Lakes precipitation was found to be best correlated with August monthly mean lake levels. This index (Quinn, 1991) was developed for the period 1860-1988. The 5 years associated with the minimum four values of the precipitation index were selected as the climate blocks to form the basis for the climate analogues.

The monthly net basin supplies for each of the Great Lakes for each 5-year scenario were developed by the component method using monthly values of precipitation, runoff, and evaporation, as shown in equation (1). Monthly recorded precipitation and runoff values were used where available. Recorded precipitation values are available for the whole period of record (1860-1988) while adequate monthly runoff values, representing the current land use patterns, are available from approximately 1950 to date. Runoff values for the period prior to 1950 were derived from a monthly version of the GLERL Large Basin Runoff Model (Croley, 1983).

Analysis of the monthly lake evaporation showed that evaporation is not correlated to either monthly temperatures or monthly precipitation, the basic data sets available prior to 1950. It was found that both extreme high and extreme low monthly evaporation could occur with the same monthly average temperature. This is because lake evaporation is an episodic phenomenon highly dependent upon cold outbreaks with cold temperatures, high wind, and low dew points passing over the relatively warm lake surfaces (Croley, 1992). For this reason it was decided to generate a statistical distribution of 5-year evaporation values based upon the recorded monthly evaporation for the 1950-1988 period using a Monte Carlo simulation technique. The 5 percent exceedance 5-year value generated from the distribution was selected for use with the low water supply scenarios to minimize the resulting water supplies. Thus, 60 monthly values representing the low scenarios were subtracted from the combined monthly precipitation and runoff values for each scenario. Thus all low scenarios had the same respective evaporation values. The selected low scenarios are shown in Table 5. The Lake Ontario net basin supplies for the 1960-1965 scenario were adjusted downward by correction factors to account for unresolved differences between the coordinated net basin supplies and those computed by equation (1). These corrections were made inorder to provide a valid comparison with the "present conditions" scenario. Supplies computed by equation (1) are not available prior to 1948, thus correction factors were not applied to the other scenarios.

Table 5. Climate Analog 5 Year Average Net Basin Supply (m^3s^{-1})

Scenario	Lake Superior	Lakes Michigan-Huron	Lake St.Clair	Lake Erie	Lake Ontario
1890 - 1895	1,419	2,928	140	577	975
1920 - 1925	1,551	2,750	103	465	713
1929 - 1934	1,765	2,594	112	372	809
1960 - 1965	1,768	2,293	76	273	559
Extreme Low	1,185	1,244	86	55	605

Table 5 shows that the 1960-1965 scenario is the most severe low scenario for the middle lakes and Lake Ontario. In the case of a similar evaluation performed to select high scenarios, all lakes had their highest values during one scenario. For perspective, and to provide a lower bound, an extreme low scenario was also developed consisting of the 5 driest years from the precipitation index arranged in descending order.

These two low scenarios were input to the modified regulation and routing model to generate lake levels and flows in the connecting channels. The results, compared to the 1960-1965 minimum "present conditions" levels are given in Table 6.

Table 6. Changes in the Minimum Lake Levels For Each Climate Analog Scenario (m)

Scenario	Lake Superior	Lakes Michigan-Huron	Lake St. Clair	Lake Erie	Lake Ontario
1960-1965	-0.05	-0.04	-0.06	-0.05	-0.23
Extreme Low	-0.40	-0.96	-0.76	-0.58	-0.80

Table 6 shows that there are relatively little differences in the minimum levels between the "present conditions" levels and those of the 1960-1965 climate analog. The extreme scenario, however, demonstrates the potential for much lower lake levels than those recorded to date based upon the existing climate.

CONCLUSIONS

Modeled impacts of climate change on Great Lakes levels show a decrease from 0.30 meters to 1.76 meters. Similarly, outflows from the lakes are reduced by 16 to 43 percent. These results are within the ranges of previously reported results. Climate analogues, based upon the present climate regime, indicate that we can reasonably expect more severe water supply conditions in the future. However, even under the most severe analogue, the decrease in Great Lakes levels is only about half that projected under climate change.

The existing regulation plans for Lake Superior and Lake Ontario were found to lack the robustness needed to specify outflows under extreme dry conditions. Simple rules of operation were added to the regulation plans for the simulation of levels and flows under climate change conditions. In reality, regulation of the lakes under extreme dry conditions or climate change would involve a very complicated decision process taking into consideration the needs of all Great Lakes interests. However, the complexity of this problem should not deter those involved in making these decisions from quantifying this process and incorporating it into future operational lake regulation plans. Although this is a policy issue, additional control structures and multiple lake regulation may be required to cope with the impacts of climate change on the Great Lakes. Additional work and research must be undertaken to better define the impacts of climate change on the Great Lakes ecosystem and the socio-economic implications for the comprehensive development of policy.

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